

# DETAILED ABUNDANCES OF PLANET-HOSTING WIDE BINARIES. I. DID PLANET FORMATION IMPRINT CHEMICAL SIGNATURES IN THE ATMOSPHERES OF HD 20782/81\*?

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## ABSTRACT

Using high-resolution, high signal-to-noise echelle spectra obtained with Magellan/MIKE, we present a detailed chemical abundance analysis of both stars in the planet-hosting wide binary system HD 20782 + HD 20781. Both stars are G dwarfs, and presumably coeval, forming in the same molecular cloud. Therefore we expect that they should possess the same bulk metallicities. Furthermore, both stars also host giant planets on eccentric orbits with pericenters  $\lesssim 0.2$  AU. Here, we investigate if planets with such orbits could lead to the host stars ingesting material, which in turn may leave similar chemical imprints in their atmospheric abundances. We derived abundances of 15 elements spanning a range of condensation temperatures ( $T_C \approx 40$ –1660 K). The two stars are found to have a mean element-to-element abundance difference of  $0.04 \pm 0.07$  dex, which is consistent with both stars having identical bulk metallicities. In addition, for both stars, the refractory elements ( $T_C > 900$  K) exhibit a positive correlation between abundance (relative to solar) and  $T_C$ , with similar slopes of  $\approx 1 \times 10^{-4}$  dex K<sup>-1</sup>. The measured positive correlations are not perfect; both stars exhibit a scatter of  $\approx 5 \times 10^{-5}$  dex K<sup>-1</sup> about the mean trend, and certain elements (Na, Al, Sc) are similarly deviant in both stars. These findings are discussed in the context of models for giant planet migration that predict the accretion of H-depleted rocky material by the host star. We show that a simple simulation of a solar-type star accreting material with Earth-like composition predicts a positive—but imperfect—correlation between refractory elemental abundances and  $T_C$ . Our measured slopes are consistent with what is predicted for the ingestion of 10–20 Earths by each star in the system. In addition, the specific element-by-element scatter might be used to distinguish between planetary accretion and Galactic chemical evolution scenarios.

*Subject headings:* planetary systems: formation — stars: abundances — stars: atmospheres — stars: individual (HD 20782, HD 20781)

## 1. INTRODUCTION

Exoplanet surveys like NASA’s *Kepler* mission are discovering planets in a variety of environments, e.g., systems with multiple stellar components, which suggests that planet formation mechanisms are remarkably robust. An important result in attempts to understand these planet formation mechanisms is that giant planets are found to be more prevalent around solar-type stars that are typically enriched in metals by  $\sim 0.15$  dex relative to similar stars that have no detected giant planets (e.g., Fischer & Valenti 2005; Ghezzi et al. 2010). This evidence indicates that giant planet formation is most successful in metal-rich environments.

Beyond overall metallicity, investigations of abundance patterns in elements besides Fe in planet-hosting stars have uncovered evidence that planet hosts may be enriched or depleted (relative to the Sun) with elements of

high condensation temperatures ( $T_C \gtrsim 900$  K, i.e., the refractory elements that are the major components of rocky planets) depending on the architecture and evolution of the their planetary systems. There are at least two planet formation processes that may alter stellar surface abundances: (1) the accretion of hydrogen-depleted rocky material (Gonzalez 1997), which would result in the *enrichment* of the stellar atmosphere, and (2) H-depleted rocky material in terrestrial planets may be withheld from the star during their formation, which would result in the *depletion* of heavy elements relative to H in the stellar atmosphere (Meléndez et al. 2009). For the enrichment scenario, Schuler et al. (2011a) suggest that stars with close-in giant planets ( $\sim 0.05$  AU) may be more enriched with elements of high condensation temperature ( $T_C$ ). This is thought to be a result of giant planets which form in the outer planetary system migrating inward to their present close-in positions. As they migrate, they can push rocky material into the host star (e.g., Ida & Lin 2008; Raymond et al. 2011). For the depletion scenario, Meléndez et al. (2009) and Ramírez et al. (2009) propose that the depletion of refractory elements in Sun-like stars may correlate with the presence of terrestrial planets. Certainly there are processes other than planet formation that may alter stellar atmospheric abundances, but these effects can be mitigated by simultaneously considering a pair of stars that have experienced essentially the same evolution and environments over the course of their

\* The data presented herein were obtained at the Las Campanas Observatory with the Magellan/MIKE spectrograph.

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lives, such as stars in wide binaries.

Indeed, wide stellar binaries known to harbor planets are valuable laboratories for studying the connection between how planets form and the chemical compositions of their host stars. Since most binary stars are believed to have formed coevally from a common molecular cloud (Kratter 2011, and references therein), planet-hosting wide binaries are particularly valuable, because both stars can be presumed to have the same age and initial composition. In fact, Desidera et al. (2004, 2006) studied the differential Fe abundances for a set of 50 wide binaries. They found that only one binary pair possessed a  $\Delta[\text{Fe}/\text{H}] > 0.09$  dex, while for the majority of the systems they found  $\Delta[\text{Fe}/\text{H}] < 0.03$  dex. Thus, for components of wide binaries where at least one star possesses a planet, it is reasonable to expect that any significant difference in their present-day chemical abundances is most likely due to some aspect of the planet formation process.

For example, the investigation by Schuler et al. (2011b) of 16 Cyg (a triple system that includes a wide binary pair of two nearly identical stars, plus the secondary hosts a giant planet at  $\sim 1.7$  AU while the primary does not) found that 16 Cyg A and 16 Cyg B were chemically identical (However, we should note that Ramírez et al. (2011) found that 16 Cyg A is more metal rich than 16 Cyg B by  $0.041 \pm 0.007$  dex, but Metcalfe et al. (2012) found that the two stars are chemically identical). The authors speculated that one possible reason 16 Cyg B formed a giant planet, while 16 Cyg A may not have, is because 16 Cyg A itself has a resolved M dwarf companion (the tertiary in the system). This third star may have truncated the primary’s circumstellar disk and inhibited planet formation (e.g., Jensen et al. 1996; Mayer et al. 2005). Since the two stars must be the same age, and in addition they were found to be chemically identical, the authors were forced to consider the properties of the system described above, which could have led to these two stellar twins failing to form planetary systems with similar architectures. The 16 Cyg wide binary was an ideal first system for this kind of comparison study, because the component stars have almost identical physical properties, i.e., their masses are nearly equal. This minimizes systematic errors that may arise from analyzing two stars with drastically different basic stellar properties (Schuler et al. 2011b).

Ascertaining how planet formation may influence the composition of host star atmospheres could revolutionize target selection for future exoplanet surveys. If chemical abundance patterns can identify a star as a planet host, then a single high-resolution spectrum—instead of solely relying on large, time-intensive monitoring surveys—will permit selection of probable planet hosts among nearby stars in our Galaxy. Furthermore, if particular chemical signatures indicate the existence of specific kinds of planets, such as terrestrial planets, considerably more targeted searches for Solar System analogs would be possible.

The goal of this series of papers is to study the interplay between planet formation and the chemical composition of the host star by directly comparing the chemical abundances of each stellar pair in planet-hosting wide binaries. This paper presents the analysis of detailed abundance trends in the two stars comprising the HD 20782/81 system. HD 20782 and HD 20781

are a common proper motion wide binary with an angular separation of  $252''$  and a projected physical separation of  $\sim 9,000$  AU (Desidera & Barbieri 2007; Mugrauer & Neuhauser 2009). They are both solar-type stars with spectral types of G1.5V and G9.5V, and apparent V magnitudes of 7.36 and 8.48, respectively (Gray et al. 2006).

For HD 20782/81 we present the investigation of the only known binary system where both stars have detected planets. HD 20782 has a Jupiter-mass planet on a very eccentric ( $e \sim 0.97$ ) orbit at  $\sim 1.4$  AU (Jones et al. 2006), and HD 20781 hosts two moderately eccentric ( $e \sim 0.1 - 0.3$ ) Neptune-mass planets within  $\sim 0.3$  AU (M. Mayor 2013, private communication). Therefore, *if* the formation and evolution of planetary systems with different architectures affect the host star composition in distinct ways, studying systems like HD 20782/81 allows us to discern which aspects of their architectures play the most important roles.

In Section 2, we describe our observations, reductions, and spectral analysis. In Section 3, we summarize the main results, including the finding that both stars in HD 20782/81 exhibit similar positive trends between refractory elemental abundance and  $T_{\text{C}}$ . In Section 4, we discuss the results in the context of previous studies and a simple calculation that predicts how the accretion of Earth-like rocky planets would affect refractory elemental abundances as a function of  $T_{\text{C}}$ . We find that the observed trends between refractory elemental abundance and  $T_{\text{C}}$ , and the element-by-element scatter relative to the mean trends, are consistent with the ingestion by both stars of 10–20 Earths. Finally, in Section 5 we highlight our main conclusions.

## 2. DATA AND ANALYSIS

For both HD 20782/81, on UT 2012 Feb 08 we obtained high-resolution, high-signal-to-noise ratio (SNR) spectra with the 6.5-m Magellan II (Clay) telescope (Shectman & Johns 2003) and MIKE echelle spectrograph (Bernstein et al. 2003). The spectra covered a wavelength range from  $\sim 3500 - 9500\text{\AA}$ . Three exposures were taken of both HD 20782 and HD 20781, with a total integration time of 540s for HD 20782 and 1200s for HD 20781. Multiple bias frames and flat field exposures were taken at the beginning of the night. A Thorium-Argon lamp exposure was taken at the beginning and end of the night for wavelength calibration. The data were reduced using standard IRAF routines.

The final reduced spectra possess a resolution of  $R = \lambda/\Delta\lambda \sim 40,000$  and SNR in the continuum region near  $\lambda 6700$  of  $\sim 600$  for HD 20781 and  $\sim 620$  for HD 20782. Sample spectra spanning the wavelength region  $\lambda 6135 - \lambda 6175$  are shown in Figure 1. A solar spectrum (sky) was also obtained for derivation of relative abundances, and has an SNR of  $\sim 610$  near  $\lambda 6700$ .

In each star, abundances of 15 elements have been derived from the observed spectra. The 2010 version of the LTE spectral analysis package MOOG (Snedden 1973) was used to perform the spectral analysis. The abundances were derived from measurements of the equivalent widths (EWs) of atomic lines using the SPECTRE analysis package (Fitzpatrick & Sneden 1987). We adopted our line list from Schuler et al. (2011a). Stellar parameters were obtained by requiring excitation and ionization balance

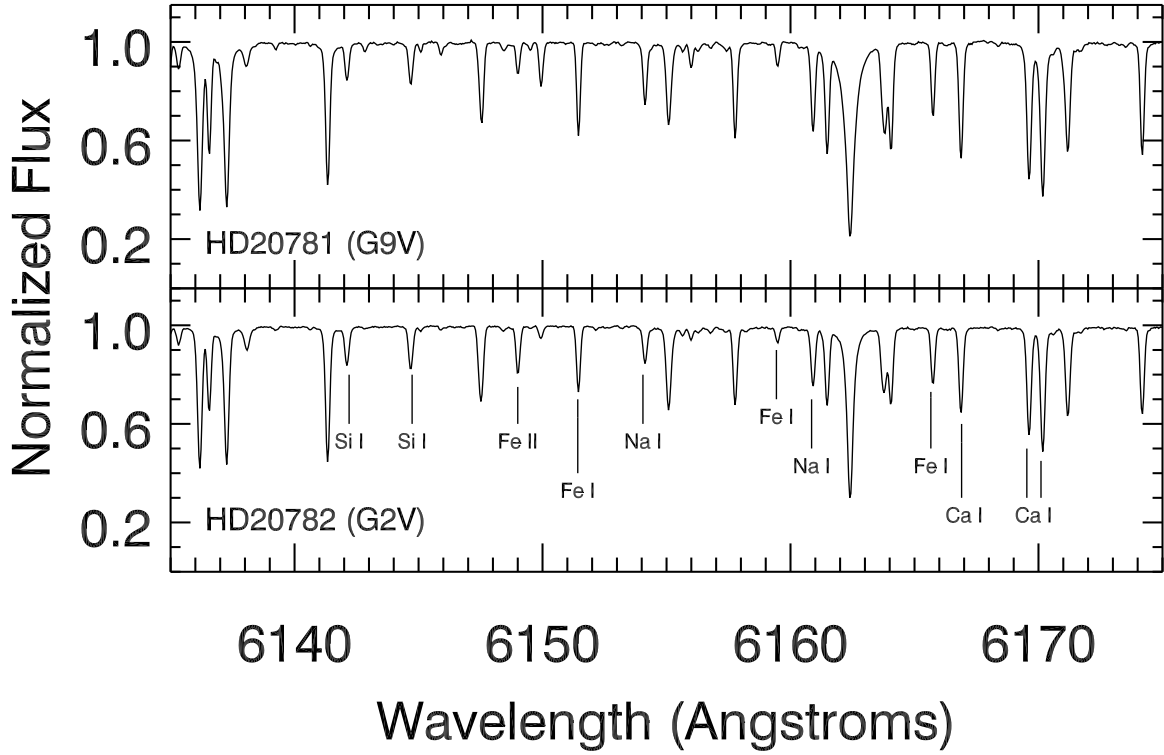


FIG. 1.— Sample Magellan/MIKE spectra for HD 20782/81, spanning the wavelength range from  $\lambda 6135 - \lambda 6175$ .

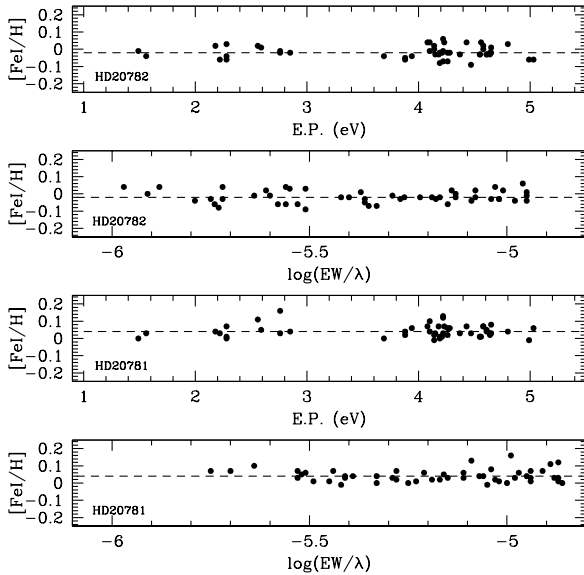


FIG. 2.— Plots of  $[\text{FeI}/\text{H}]$  vs excitation potential and reduced equivalent width for both HD 20782/81. The dashed lines indicate the mean values of  $[\text{FeI}/\text{H}]$ , which are  $-0.02$  dex and  $+0.04$  dex for HD 20782 and HD 20781, respectively.

of the Fe I and Fe II lines in the standard way. Plots of  $[\text{FeI}/\text{H}]$  vs. excitation potential and reduced equivalent width are provided in Figure 2, which shows that the correlations are zero as required. The atomic excitation energies ( $\chi$ ) and transition probabilities ( $\log gf$ ) were

TABLE 1  
STELLAR PARAMETERS & ABUNDANCES<sup>a</sup>

	HD 20782	HD 20781
$T_{\text{eff}}$ (K)	$5789 \pm 38$	$5324 \pm 52$
$\log g$ (cgs)	$4.41 \pm 0.12$	$4.51 \pm 0.10$
$\xi$ ( $\text{km s}^{-1}$ )	$1.32 \pm 0.10$	$1.02 \pm 0.11$
$[\text{C}/\text{H}]$ ...	$-0.07 \pm 0.03^b \pm 0.04^c$	$-0.09 \pm 0.03 \pm 0.04$
$[\text{O}/\text{H}]$ ...	$+0.04 \pm 0.01 \pm 0.05$	$-0.08 \pm 0.04 \pm 0.07$
$[\text{Na}/\text{H}]$ ...	$-0.08 \pm 0.02 \pm 0.03$	$-0.06 \pm 0.03 \pm 0.05$
$[\text{Mg}/\text{H}]$ ...	$+0.04 \pm 0.01 \pm 0.06$	$+0.10 \pm 0.00 \pm 0.05$
$[\text{Al}/\text{H}]$ ...	$-0.01 \pm 0.00 \pm 0.02$	$+0.04 \pm 0.00 \pm 0.03$
$[\text{Si}/\text{H}]$ ...	$-0.02 \pm 0.01 \pm 0.02$	$-0.01 \pm 0.01 \pm 0.02$
$[\text{Ca}/\text{H}]$ ...	$+0.04 \pm 0.01 \pm 0.05$	$+0.06 \pm 0.03 \pm 0.06$
$[\text{Sc}/\text{H}]$ ...	$-0.03 \pm 0.02 \pm 0.06$	$+0.04 \pm 0.02 \pm 0.05$
$[\text{Ti}/\text{H}]$ ...	$+0.06 \pm 0.01 \pm 0.05$	$+0.12 \pm 0.02 \pm 0.06$
$[\text{V}/\text{H}]$ ...	$-0.01 \pm 0.01 \pm 0.04$	$+0.10 \pm 0.02 \pm 0.07$
$[\text{Cr}/\text{H}]$ ...	$-0.05 \pm 0.01 \pm 0.03$	$+0.03 \pm 0.02 \pm 0.05$
$[\text{Mn}/\text{H}]$ ...	$-0.01 \pm 0.06 \pm 0.07$	$+0.04 \pm 0.05 \pm 0.07$
$[\text{Fe}/\text{H}]$ ...	$-0.02 \pm 0.01 \pm 0.02$	$+0.04 \pm 0.01 \pm 0.03$
$[\text{Co}/\text{H}]$ ...	$-0.05 \pm 0.01 \pm 0.03$	$+0.03 \pm 0.01 \pm 0.04$
$[\text{Ni}/\text{H}]$ ...	$-0.02 \pm 0.01 \pm 0.03$	$+0.01 \pm 0.01 \pm 0.03$

<sup>a</sup> Adopted solar parameters:  $T_{\text{eff}} = 5777$  K,  $\log g = 4.44$ , and  $\xi = 1.38$   $\text{km s}^{-1}$ .

<sup>b</sup>  $\sigma_{\mu} = \sigma/\sqrt{N-1}$ , where  $\sigma$  is the standard deviation and  $N$  is the number of lines measured for a given element.

<sup>c</sup>  $\sigma_{T_{\text{total}}}$ —quadratic sum of  $\sigma_{\mu}$  and uncertainties in the elemental abundance resulting from uncertainties in  $T_{\text{eff}}$ ,  $\log g$ , and  $\xi$ .

taken from the Vienna Atomic Line Database (VALD; Piskunov et al. 1995; Kupka et al. 1999). For each element, the abundances were determined relative to solar via a line-by-line differential analysis.

Carbon abundances are also derived with the *synth*

TABLE 2  
LINES MEASURED, EQUIVALENT WIDTHS, AND ABUNDANCES

Element	$\lambda$	$\chi$	$\log gf$	$EW_{\odot}$	$\log N_{\odot}$	$\log N_{\odot, \text{synth}}^a$	HD 20782			HD 20781		
	(Å)	(eV)					EW	$\log N$	$\log N_{\text{synth}}$	EW	$\log N$	$\log N_{\text{synth}}$
C I	5052.17	7.68	-1.304	36.2	8.51	...	36.1	8.50	...	17.2	8.35	...
C2	5086	...	...	...	...	8.43	...	...	8.32	...	...	8.35
C2	5135	...	...	...	...	8.44	...	...	8.36	...	...	8.43
C I	5380.34	7.68	-1.615	22.8	8.54	...	20.8	8.47	...	10.9	8.44	...
O I	6300.30	0.00	-9.717	5.5	8.69	...	6.3	8.72	...	6.5	8.52	...
O I	7771.94	9.15	0.369	65.6	8.77	...	71.2	8.84	...	34.7	8.71	...
O I	7774.17	9.15	0.223	57.8	8.79	...	60.5	8.82	...	30.4	8.74	...
O I	7775.39	9.15	0.001	46.5	8.80	...	47.5	8.81	...	23.1	8.75	...
Na I	5682.63	2.10	-0.700	119.9	6.52	...	107.9	6.41	...	135.1	6.41	...
Na I	6154.23	2.10	-1.560	38.2	6.31	...	33.2	6.23	...	49.2	6.23	...
Na I	6160.75	2.10	-1.260	58.1	6.31	...	53.9	6.26	...	76.4	6.31	...
Mg I	5711.09	4.35	-1.833	100.8	7.56	...	102.0	7.59	...	128.3	7.66	...
Mg I	6841.19	5.75	-1.610	64.1	7.85	...	66.0	7.89	...	74.6	8.14 <sup>b</sup>	...
Al I	6696.02	3.14	-1.347	36.7	6.24	...	34.9	6.23	...	52.7	6.28	...
Al I	6698.67	3.14	-1.647	20.7	6.21	...	19.8	6.20	...	32.6	6.25	...

NOTE. — This table is published in its entirety in the online journal. A portion is shown here for guidance regarding its form and content.

<sup>a</sup> Indicates the  $\log N$  abundance determined from the synthetic fit to a given line.

<sup>b</sup> The  $\log N$  abundance for this line was rejected as spurious, as described in paragraph 4 of Section 2.

driver in MOOG to synthetically fit the C<sub>2</sub> features at  $\lambda$ 5086 and  $\lambda$ 5135. Oxygen abundances were determined with the MOOG *blends* driver for the forbidden line at  $\lambda$ 6300, and EW measurements of the near-infrared triplet at  $\lambda$ 7771,  $\lambda$ 7774, and  $\lambda$ 7775. Also, we suspect that the Mg I line at  $\lambda$ 6841.19 is blended with a line that becomes stronger in stars with  $T_{\text{eff}} \lesssim 5400$  K, and thus we rejected the Mg abundance it yielded for HD 20781 as spurious.

For the odd-Z elements V, Mn, and Co, the abundances of which can be overestimated due to hyper-fine structure (hfs) effects (Prochaska & McWilliam 2000), spectral synthesis incorporating hfs components has been used to verify the EW-based results. The hfs components for these elements were obtained from Johnson et al. (2006), and the line lists for wavelength regions encompassing each feature were taken from VALD. The adopted V, Mn, and Co abundances are derived from the hfs analysis and those lines with EWs that were not significantly altered by hfs.

The abundance and error analyses for all elements are described in detail in Schuler et al. (2011a). The stellar abundances (relative to the solar abundances derived from the solar spectrum), parameters, and uncertainties for HD 20782/81 are summarized in Table 1. The adopted line list, EWs, and line-by-line abundances of each element for HD 20782/81 and the Sun are given in Table 2.

### 3. RESULTS

As shown in Table 1, the stellar parameters we determined for HD 20782/81 are consistent with the primary being a  $\sim$ G2V and the secondary being a  $\sim$ G9.5V. The differences in parameters (in the sense of primary minus secondary) are:  $\Delta T_{\text{eff}} = +465 \pm 64$  K,  $\Delta \log g = -0.10 \pm 0.16$  dex, and  $\Delta \xi = +0.30 \pm 0.15$  km s<sup>-1</sup>. Furthermore, according to the PASTEL catalogue of stellar parameters (Soubiran et al. 2010), the mean literature values for the stellar parameters of HD 20782 ( $T_{\text{eff}} \sim 5800$  K,  $\log g \sim 4.4$  dex, and  $[\text{Fe}/\text{H}] \sim -0.06$  dex) are in good agreement with ours. For HD 20781, our values agree

with the mean literature values for  $T_{\text{eff}}$  ( $\sim 5300$  K) and  $\log g$  ( $\sim 4.4$  dex), but there is a considerable spread of  $\sim 0.2$  dex ( $-0.18$ — $+0.01$  dex) in the published  $[\text{Fe}/\text{H}]$  values for this star. The upper end of this range is consistent with the value of  $[\text{Fe}/\text{H}]$  that we derive for HD 20781. The abundances of the 15 individual elements are shown graphically in Figure 3. The abundance differences shown in Figure 3 are the means of the line-by-line differences for each element. The mean abundance difference is  $0.04 \pm 0.07$  dex, as expected for coeval stars in a binary system.

The abundances of HD 20782/81 are shown versus  $T_C$  in Figures 4 and 5. The condensation temperatures were taken from the 50%  $T_C$  values derived by Lodders (2003). Only the refractory elements ( $T_C \gtrsim 900$  K) are displayed, because it is among these elements that the chemical signature of planet formation has been shown to be strongest (Meléndez et al. 2009). We performed both unweighted and weighted linear fits to the  $[\text{X}/\text{H}]$  versus  $T_C$  abundance relations to investigate possible correlations. For our analysis and discussion, we adopt the *weighted* fits. However, in Figure 4, we provide the unweighted fits for comparisons to previous studies that only reported unweighted fits.

As can be seen in Figures 4-5, the slopes of the unweighted linear least-squares fits are:  $m_{82} = (10.59 \pm 5.17) \times 10^{-5}$  dex K<sup>-1</sup> and  $m_{81} = (14.55 \pm 5.94) \times 10^{-5}$  dex K<sup>-1</sup> for HD 20782 and HD 20781 respectively. The slopes of the weighted linear least-squares fits are:  $m_{82} = (9.71 \pm 4.57) \times 10^{-5}$  dex K<sup>-1</sup> and  $m_{81} = (13.60 \pm 6.57) \times 10^{-5}$  dex K<sup>-1</sup> for HD 20782 and HD 20781 respectively. Thus the correlation between refractory elemental abundance and  $T_C$  is not perfect, with individual elements exhibiting scatter relative to the mean trend. Nonetheless, the slopes of the weighted linear fits to refractory abundances vs  $T_C$  are modestly statistically significant ( $\sim 2\sigma$ ). In addition, both a Pearson's  $r$  and a Kendall's  $\tau$  correlation test indicate that the abundances and  $T_C$  are correlated at  $> 90\%$  confidence for both stars (Pearson  $r$



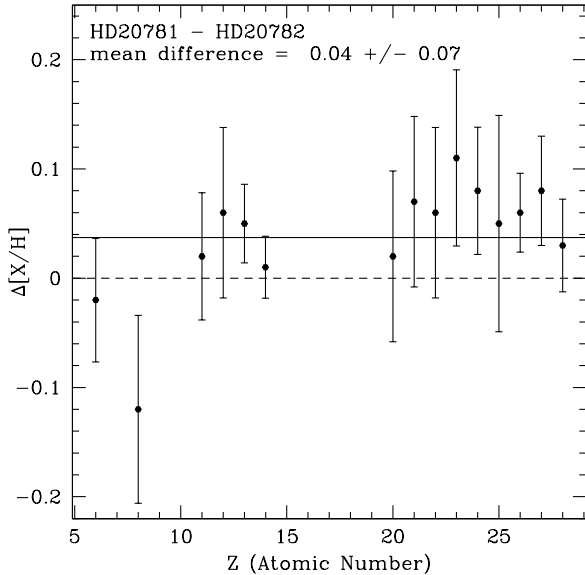


FIG. 3.— Differential abundances for HD 20782/81 as a function of atomic number ( $Z$ ). The solid line represents the mean difference of  $0.04 \pm 0.07$  dex, and the dashed line is meant to guide the eye at 0.0 dex.

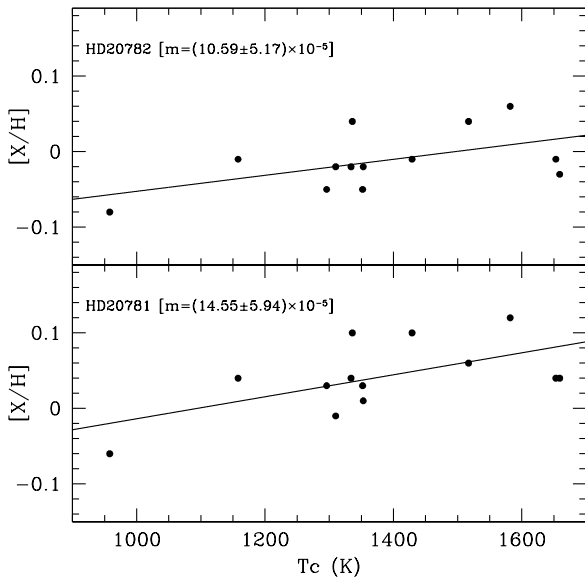


FIG. 4.— Unweighted linear fits to abundance vs. condensation temperature ( $T_C$ ) for HD 20782/81.

confidence of 97% for HD 20781 and 92% for HD 20782).

In the discussion that follows, we consider this result in the context of a model to predict the degree to which we might expect a modest correlation between abundance and  $T_C$  from host stars that have ingested a small amount of rocky planetary material.

#### 4. DISCUSSION

##### 4.1. How well correlated are abundance and $T_C$ expected to be?

To estimate the impact that the accretion of a rocky planet would have on the atmospheric composition of a solar-type star, we simulated the accretion of a massive body with Earth-like composition onto the Sun. Since Jupiter and Saturn are predominantly composed of H and He with approximately solar H/He ratios (Young 2003; Lissauer & Stevenson 2007), the chemical composition of a gas giant planet is likely to be fairly similar to the protoplanetary disk, and thereby to the host star. The accretion of gas giant planets, therefore, would be unlikely to produce the refractory element versus  $T_C$  correlation observed in some planet hosts. Such trends would be expected to arise only from the accretion of H-depleted rocky material.

To perform our calculation of the expected trend between refractory elemental abundance and  $T_C$ , we begin by considering what would happen to the refractory abundances of the Sun if it accreted a certain multiple of  $M_\oplus$  of refractory material with a composition similar to the Earth. Since the metallicities of HD 20782/81 are consistent with solar (all elemental abundances are within  $\sim 0.1$  dex of their solar values) it is reasonable to assume that the primordial abundances of both stars were similar to the present-day solar abundances. We use the values of McDonough (2001) to obtain the mass fraction for each element in the Earth. With the mass of the Earth, and the molar mass for each element, we can determine an absolute number of atoms for each element. Then we add this amount of each element into the solar convection zone and see how the abundances change. Given the mass of the Sun, the mass fraction of hydrogen, and the fact that at 30 Myr (by which time gas should have dissipated from the protoplanetary disk, and only fully formed planets and a debris disk remain) the convection zone was 3% of the Sun's mass (Sackmann et al. 1993), we can determine the amount of hydrogen in the Sun's convection zone at that time. Using the solar abundances listed in Asplund et al. (2009), the photospheric abundance of each element relative to hydrogen can be determined. Thus, the change in the abundance of each element due to the accretion of a certain multiple of  $M_\oplus$  of Earth-like rocky material can be calculated.

Through the order-of-magnitude calculation described above, we derived the values for the  $[X/H]-T_C$  slopes in each of the accretion scenarios shown in Figure 6. For example, if a solar-type star were to accrete  $5M_\oplus$  of material with a chemical composition similar to the Earth, then from our calculation we would expect a trend with  $T_C$  among the refractories that corresponds to a slope of  $(5.42 \pm 1.62) \times 10^5$  dex  $K^{-1}$  (Figure 6). Furthermore, as a result of our simulation of a Sun-like star accreting Earth-like planets, we would *not* expect a perfect correlation between abundance and  $T_C$ . There is some scatter about the linear fit to the simulated data, as shown in Figure 6. Indeed, some of the elements deviate in a similar manner from the linear fit in both the observed and modeled data. For example, in Figures 4–6, the elements Na ( $T_C \sim 960$  K), Al ( $T_C \sim 1653$  K), and Sc ( $T_C \sim 1659$  K) are consistently below the fits to both the simulated and observed data. Since these elements are similarly scattered about the fit in both the model and the observations, the scatter in the observed correlation may not solely be the result of observational noise.

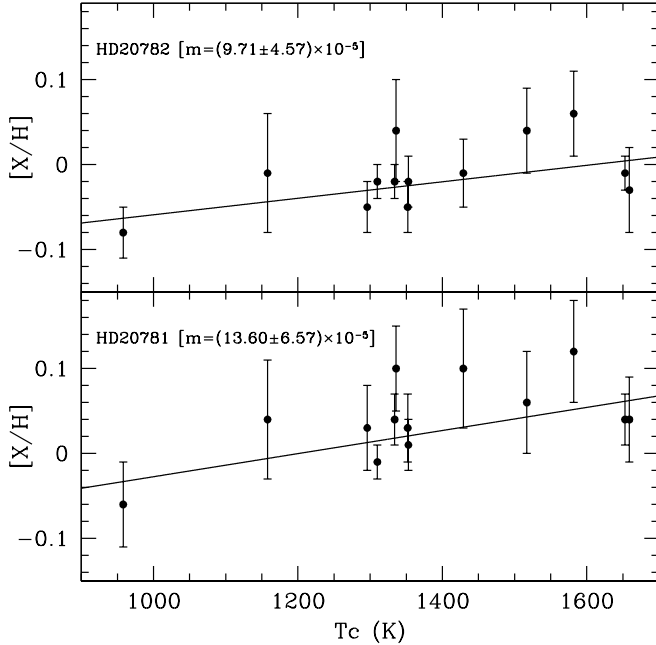


FIG. 5.— *Weighted* linear fits to abundances vs. condensation temperature ( $T_c$ ) for HD 20782/81.

There are several ways to extend the above calculation, for example, to take into account differences in the mass of the star, the mass-dependence of the size of the convection zone, and possible variations in the composition of the planets accreted by the star. Such additional considerations could perhaps explain additional scatter in the observed abundances. Here our intent is to illustrate the sense and magnitude of the effect. However, given that  $\Delta T_{\text{eff}} = +465 \pm 64$  K for HD 20782/81, we investigated how differences in the depths of their convection zones would affect the results of our simple model. Using Figure 1 from Pinsonneault et al. (2001), which provides a relationship between  $T_{\text{eff}}$  and the mass of the convection zone, we estimate that for a star like HD 20781 ( $T_{\text{eff}} \sim 5300$  K) the mass of the convection zone is at most  $\sim 0.05 M_\odot$ . Using the empirical relationships described in Torres et al. (2010)—which yield the mass and radius of a star as functions of the spectroscopic stellar parameters—we can estimate the mass of HD 20781 to be  $\sim 0.9 M_\odot$ . This means that about 6% of the mass of HD 20781 is in the convection zone (as opposed to  $\sim 3\%$  for stars with masses similar to the Sun). Thus, while our simulation shows that the ingestion of  $10 M_\oplus$  of Earth-like material would produce the measured slope for HD 20782, about twice as much material is required to produce the measured slope for HD 20781 (Figure 6).

#### 4.2. Interpretation of the positive slopes for HD 20782/81

The positive trends with  $T_c$  seen among the refractory elemental abundances of HD 20782/81 may be due to the presence of eccentric giant planets that have migrated to orbits within  $\sim 1$  AU. HD 20782 hosts a very eccentric Jupiter at 1.4 AU, with a pericenter of  $a(1-e) = 1.4(1-0.97) \sim 0.04$  AU. HD 20781 possesses two close-in Neptunes at 0.2 and 0.3 AU. These giant planets could have pushed refractory-rich planetary material into their

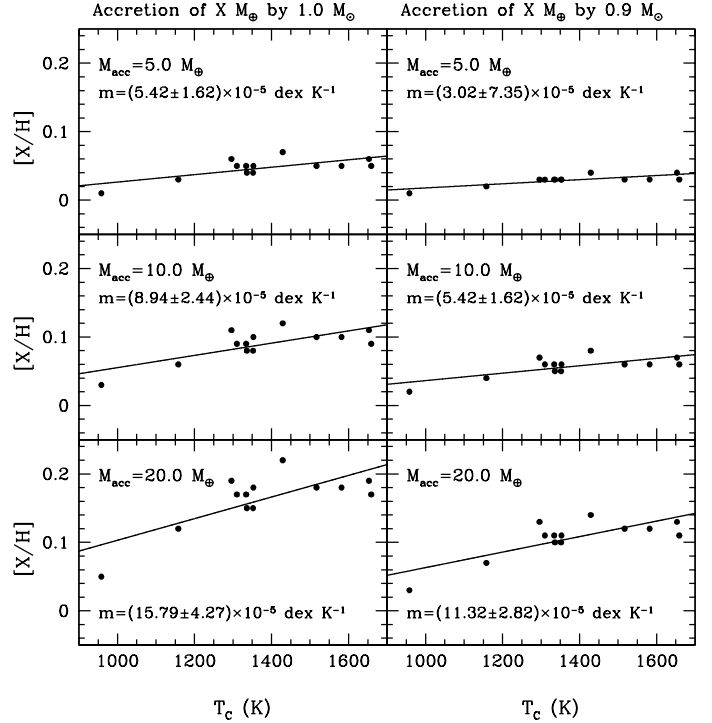


FIG. 6.— *Unweighted* linear fits to simulated abundances vs. condensation temperature ( $T_c$ ) from our modeled accretion of  $X$  amount of  $M_\oplus$  by a solar-composition star (see Section 4.1). The *left* panel shows the results for the accretion of 5, 10, and 20  $M_\oplus$  by a  $1.0 M_\odot$  star, and the *right* panel shows the results for the accretion of the same three amounts of Earth-like material, but for a  $0.9 M_\odot$  star.

host stars as they migrated inward to their current orbits. We have shown in Section 4.1 that compared to a simple model of a solar-type star accreting Earth-like material, both HD 20782/81 have slopes that are consistent with the ingestion of  $10 - 20 M_\oplus$  of rocky material.

Several studies have performed simulations of giant planet migration that result in a substantial amount of hydrogen-depleted material falling into the star (e.g., Ida & Lin 2008; Raymond et al. 2011). This usually occurs because of planet-planet scattering in a rocky debris disk after the gas-rich protoplanetary disk has dissipated. Raymond et al. (2011) found that in 40% of their simulations, giants migrating in debris disk as a result of planet-planet scattering removed all rocky material from the planetary system, most of which was accreted by the host star. Furthermore, for giant planets with a minimum orbital distance less than  $\sim 1$  AU, all terrestrial material was destroyed. Both of the planets around HD 20781 have semi-major axes  $\lesssim 0.3$  AU, and the eccentric planet hosted by HD 20782 has a perihelion distance of only  $\sim 0.04$  AU. Therefore the simulations performed by Raymond et al. (2011) indicate that both planetary systems should be devoid of rocky material.

In addition, Kaib et al. (2013) also noted that over billions of years planets can be driven into their host stars because of the presence of a wide binary companion and Kozai resonances. As the binary pair orbits the galaxy, galactic tides can perturb the binary system and change the pericenter. At closest approach, each star can disrupt any planetary system that may exist around its binary companion. When Kaib et al. (2013) com-

pared HD 20782/81 to wide binaries in their simulations with similar masses and semimajor axes, they found that  $\sim 55\%$  of the systems like HD 20782/81 triggered instabilities, and more than 90% of those instabilities occurred in the planetary system after 100 Myr. These instabilities resulted in planets colliding with the star 14% of the time. Therefore, both perturbations of the stellar binary as well as planetary migration through planet-planet scattering can lead to the ingestion of planetary material by the host star, and thereby generate the abundance patterns which are present in our data and predicted by our accretion model.

#### 4.3. Comparison to previous work

Our findings, namely that the positive trends with  $T_C$  for the refractory elements indicate that both HD 20782/81 have accreted H-depleted, refractory-rich material, are consistent with the interpretations of Schuler et al. (2011a); Schuler et al. (2011b); Meléndez et al. (2009); Ramírez et al. (2009). In particular, Schuler et al. (2011a) analyzed abundances versus  $T_C$  trends for 10 stars known to host giant planets. The trends with  $T_C$  for these 10 stars were compared to a sample of 121 stars with and without detected giant planets from Gonzalez et al. (2010); the distribution of slopes with respect to  $[\text{Fe}/\text{H}]$  for the  $\sim 120$  stars from the Gonzalez et al. (2010) sample was interpreted as the general trend from Galactic chemical evolution. Of the 10 stars investigated by Schuler et al. (2011a), the four with very close-in ( $\sim 0.05$  AU) giant planets were found to have positive slopes that lie above the Galactic trend. HD 20782/81 also have positive slopes that lie above this Galactic trend. The four stars from Schuler et al. (2011a) were also hypothesized to have ingested refractory-rich planetary material as a result of the evolution of their planetary systems. However, González Hernández et al. (2013) analyzed a sample of 61 late-F to early-G stars, 29 of which have detected planets and 32 do not. After correcting their trends with  $T_C$  for Galactic chemical evolution, they found that their stars with and without detected planets possessed similar  $[\text{X}/\text{H}]-T_C$  slopes. Therefore, they concluded that, in general, trends with  $T_C$  may not indicate the presence or absence of planets.

Part of the value of comparing coeval stars in wide binaries, is that any *difference* in their abundance trends is most certainly not the result of Galactic chemical processes. However, since HD 20782/81 exhibit *similar* abundance trends, this finding could in fact either be the result of the planet formation process or Galactic chemical evolution. In order to distinguish between these two scenarios, we compared the  $[\text{X}/\text{H}]-T_C$  slopes for HD 20782/81 to the distribution of slopes observed for the  $\sim 120$  stars in the Gonzalez et al. (2010) sample. Among the stars within 0.1 dex of solar metallicity in this sample, the slopes of HD 20782/81 lie in the upper envelope of the distribution of slopes, which suggests that they are on the higher end of the Galactic trend. Furthermore, the fact that they both deviate from the Galactic trend in the same way also suggests that their abundances have most likely been changed by a similar process, i.e., the accretion of rocky planetary material. Finally, it is not obvious that Galactic chemical evolution can produce the specific element-by-element scatter that

we observe (e.g., Na, Al, Sc, see Section 4.1), whereas the planet accretion scenario appears to reproduce it naturally, at least in our current simple model (Section 4.1).

Meléndez et al. (2009) and Ramírez et al. (2009) have performed studies of solar twins (stars with physical parameters nearly identical to the Sun), and found that solar refractory abundances decrease as a function of  $T_C$ . Therefore, since the Sun formed terrestrial planets, they posit that a negative slope may indicate the presence of terrestrial planets, which contain the refractory-rich, H-depleted material that would have otherwise been accreted by the host star. Since we can rule out negative slopes for both HD 20782/81 at the  $2\sigma$  level, the interpretation suggested by Meléndez et al. (2009) and Ramírez et al. (2009) implies that neither star hosts terrestrial planets, which, as noted previously for planetary systems with giant planets at  $\lesssim 1$  AU, is consistent with models of planet migration that predict that both HD 20782/81 are unlikely to host rocky planets (Veras & Armitage 2005; Raymond et al. 2011).

Unlike the work performed by Schuler et al. (2011a) on planet-hosting field stars, or the work by Meléndez et al. (2009) and Ramírez et al. (2009) on solar twins culled from a sample of field stars, or even the work by Schuler et al. (2011b) and Ramírez et al. (2011) on 16 Cyg, this paper’s focus on HD 20782/81 permits the comparison of two coeval stars that *both* have detected planetary systems. The Kozai mechanism that is likely the source of the large eccentricity of 16 Cyg B b (Holman et al. 1997; Mazeh et al. 1997; Takeda & Rasio 2005), is most likely the cause of the very high eccentricity of HD 20782 b as well. However, in the multiplanetary system hosted by the secondary star, the two planets HD 20781 b/c can dynamically interact with each other to suppress the effect of the Kozai mechanism, and prevent highly eccentric orbits (Innanen et al. 1997; Batygin et al. 2011; Kaib et al. 2011). Thus, while the architectures of the planetary systems hosted by HD 20782/81 are not identical, the fact that both stars possess giant planets with pericenters  $\lesssim 0.2$  AU probably resulted in the injection of  $10 - 20 M_\oplus$  of Earth-like rocky material into both stars.

#### 5. CONCLUSION

We have performed a detailed chemical abundance analysis of the planet-hosting wide binary HD 20782/81, which is presently the only known wide binary where both stars have detected planets. The mean element-to-element abundance difference between the two stars is  $0.04 \pm 0.07$  dex, signifying that their bulk metallicities are identical, as expected for a binary system. Both stars show modestly significant ( $\sim 2\sigma$ ) positive trends with  $T_C$  among their refractory elemental abundances. We cannot definitively rule out that these trends may be the result of Galactic chemical evolution. However, given the orbital characteristics of the stellar binary, and the fact that both stars have eccentric giant planets that approach within  $\lesssim 0.2$  AU, models of dynamical interactions between binary stellar companions and models of giant planet migration indicate that the host stars could have accreted rocky planetary bodies that would have initially formed interior to the giant planets. This is also consistent with previous studies that found positive trends with  $T_C$  in field stars with close-in giant planets.

According to our simple model for the accretion of Earth-like planets, the slopes of the weighted fits to these trends are consistent with HD 20782 accreting  $\sim 10 M_{\oplus}$  and HD 20781 accreting  $\sim 20 M_{\oplus}$  of material with Earth-like composition. Our model also predicts that there should not be a perfect correlation between refractory abundances and  $T_C$  for stars accreting H-depleted, rocky planetary material. Three elements (Na, Al, and Sc) are similarly discrepant with both the fit to the simulated data and the fit to the observed data. Therefore, the scatter in the  $[X/H]-T_C$  correlation is not necessarily due solely to observational noise, but may in fact be a signature of the accretion of refractory-rich material driven by the inward migration of the giant planets orbiting these stars. Indeed, the specific character of the element-by-element scatter might be used as a strong dis-

criminant between the planetary accretion and Galactic chemical evolution scenarios. As we investigate other planet-hosting wide binaries, we hope to further refine these insights into abundances trends and their relation to the planet formation process.

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